Fermi National Accelerator Laboratory

TM-1577

Single Bunch Intensity Monitoring System Using an Improved Wall Current Monitor*

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March 1989

* Presented by R. Webber at the 1989 IEEE Particle Accelerator Conference, Chicago, Illinois, March 20-23, 1989.

Operated by Universities Research Association, Inc., under contract with the United States Department of Energy

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ABSTRACT

Important parameters in collider operations are the length and intensity of individual beam bunches. A system to automatically measure these parameters has been developed using a wall current monitor signal digitized by a 1 GHz sampling oscilloscope under microprocessor control. Bunch length and intensity are computed by the microprocessor and presented to the host computer. To verify the required accuracy, attention has been paid to the calibration and frequency response of the system. Design and performance of a new wall current monitor with improved bandwidth is presented.

INTRODUCTION

The luminosity during colliding beams operation depends directly upon the product of the intensities of the colliding bunches and upon the longitudinal distribution of particles within the bunch. Bunch intensity and length in terms of a gaussian fit are used to estimate the luminosity according to equation (1).

$$L \;\alpha\; N_i * N_j * F(\sigma_i,\sigma_j) \tag{1}$$

N_i = intensity of the ith bunch

σ_i = bunch length sigma

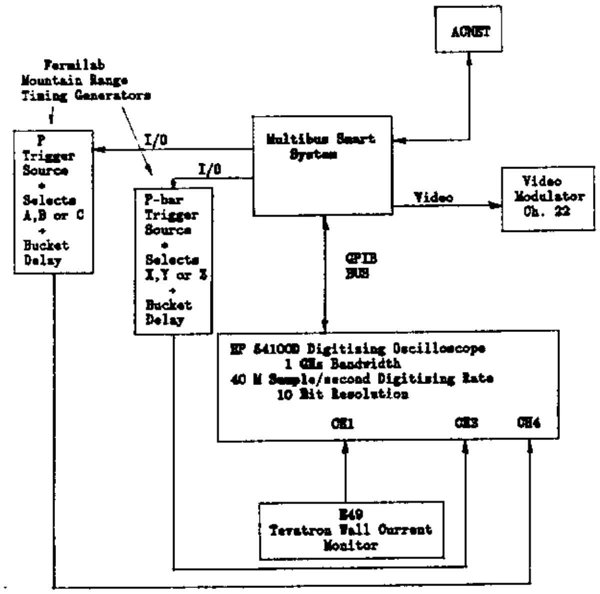

Fig. 1 Overview of the Tevatron SBD System.

The Sampled Bunch Display, or SBD, is the name applied to a system which can locally acquire and compute the intensity and longitudinal distribution of a beam bunch and make these parameters available to the accelerator control system network, or ACNET. After the longitudinal intensity profile of a given bunch has been acquired by the Hewlett Packard 54100D oscilloscope from a wall current monitor, the bunch profile is processed. The processing is performed by a Motorola 68000 microprocessor which calculates the intensity, and several parameters describing the longitudinal distributions. In a 6x6 store the local program automatically adjusts the trigger timing and acquires data for all of the proton and antiproton bunches. An overview of the Tevatron SBD system is provided in Fig. 1.

WALL CURRENT MONITORS

Resistive wall monitors consist basically of a resistive gap along a conducting beam pipe. Charged particles traveling inside the pipe drag an equal yet opposite image charge with them along the inside surface. When this image current passes through the resistive gap a signal is produced. A ferrite core is placed around the gap to prevent beam induced ac currents from flowing through stray electrical connections across it. An electrical shield is placed around the outside of the ferrite to shunt external noise currents around the gap impedance. A sketch and electrical equivalent circuit of a resistive wall monitor are shown in Fig. 2.

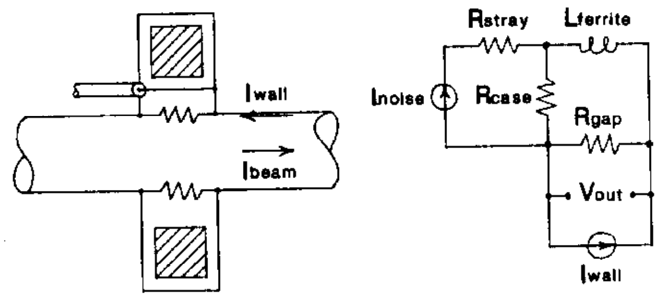

Fig. 2 Basic resistive wall monitor with equivalent circuit.

In order to provide a signal for the SBD system in a timely fashion, resistive wall monitors for both the Main Ring and Tevatron were built using existing parts. New style monitors are being designed to replace these and for use in the Linac, Booster, and P-bar accelerators. The new style will provide a direct comparison of the various beams and offer significantly improved bandwidth and fidelity.

A ceramic break is used to span the gap allowing the resistive material and ferrite to reside outside of the accelerator vacuum. The Main Ring uses a 6 inch diameter ceramic break with .5 inch length and .25 inch wall. To form the resistance, 102 33 Ω axial lead carbon resistors are evenly spaced around the circumference. For the Tevatron, the ceramic break has a 4.75 inch diameter, .5 inch length, .375 inch wall, and the resistance is formed with 158 51 Ω resistors. The gap resistance was selected to be much smaller than the changes of impedance with frequency of the parallel ferrite loaded cavity. The low frequency response, dominated by the gap resistance and the inductance provided by the ferrite, has a corner frequency of a few KHz for both detectors.

For a beam traveling along the center of the pipe, the effect of the ceramic break can be modeled as a

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radial transmission line. If the wall thickness of the ceramic is small, the characteristic impedance will be nearly constant and given by equation (2).

$$Zo = \frac{377*lgap}{\sqrt{\epsilon r}*\pi*dgap} \quad (2)$$

The length of the ceramic is represented by lgap and the diameter by dgap. With a relative permitivity of ϵr=8.9 for the ceramic, Zo becomes 4.2 Ω for the Tevatron detector. The ceramic break used for the Tevatron is 1/4 wavelength thick at 1.9 GHz. At this frequency the ratio of voltage across the resistors on the outside of the ceramic to the beam image current on the inside of the ceramic becomes Zo/Zg, where Zg represents the gap impedance. This model agrees with measurement in predicting a 20db peak at 1.9 GHz in the transfer function for the Tevatron detector which has a gap impedance of .32 Ω. At 1 GHz there is a 3db rise which partially corrects cable attenuation and the roll off of the oscilloscope.

For a beam traveling off center, the image current will not be uniform around the azimuth of the gap. Position detectors have been built using this principle [1]. With one monitor point on the Tevatron detector, the amplitude of a 2.8 nsec wide pulse was measured to vary by a factor of 2 as the position ranged over the center half of the aperture. This is reduced to 3% variation by summing the signal from 3 equally spaced points around the circumference. The Main Ring detector was built with 4 monitor points and has only a 1.5% variation.

Resistive combiners were selected to perform the summation of the monitor points. They provide superior bandwidth and accuracy over reactive combiners. Using selected carbon resistors, bandwidths of dc to 5 GHz with less than 1db amplitude variation are easily obtainable. At the monitor points, one of the normal gap resistors is replaced with a 50 Ω cable maintaining the azimuthal uniformity of the gap. One property of resistive combiners is that they require reverse termination. This becomes difficult as the impedance of the gap from a single point is proportional to the square root of the frequency. We found that keeping the transmission lines short and placing a series 5 to 10 Ω resistor at the gap provides sufficient frequency response.

A significant amount of noise can enter the output signal from inside the beam pipe. When a charged particle passes discontinuities in the vacuum chamber electromagnetic waves are launched in both directions. The frequency components above cutoff in the beam pipe can propagate significant distances. The energy in these modes creates currents in the beam pipe walls which the resistive wall detector will dutifully report. Measurements in the Main Ring indicate the dominant frequencies involved are at 1.8 GHz and cover a relatively broad spectrum. At times, the noise levels can approach 10% of the beam signal. To suppress the amount of noise current reaching the detector, microwave absorbing material was placed inside the vacuum pipe upstream and downstream of the detector. A reduction of more than 20db was realized.

The detector system including resistive wall monitor, cables, splitters, and the measurement scope have less than ideal response. Although the variation with frequency is only a few db from 1.5 KHz to 1 GHz it still represents a significant error for the calculation of bunch intensities. In order to calibrate the system we compared the SBD readings for a bunch like signal injected directly into the scope with the readings for the same pulse injected into the detector in the tunnel. There was good agreement of the combined component measurement with the SBD system after a 10% error was found in the accuracy of the HP sampling scope. The absolute accuracy was verified by comparing the area measured with a Tektronix 7104 oscilloscope to that calculated with the SBD system. The 7104 was first calibrated with a precision dc voltage source and a frequency counter. To determine the pulse area, several photographs of the scope trace were taken and measured with a digitizing tablet connected to a computer.

A new resistive wall current monitor design is being developed, and the first prototype has been built. The dimensions of the ceramic have been reduced to allow the proper termination of the radial mode and thus improve the frequency response. The ceramic gap length is .125 inches with a .188 inch wall and 3.75 inch diameter. To reduce and control stray reactances, the carbon composition resistors spanning the gap and in the combiner circuit have been replaced with chip resistors. Four 68 Ω microstrip transmission lines equally spaced around the circumference are used to extract the signal and 48 70.7 Ω resistors are used to form the gap resistance. The combination of the 48 chip resistors and 4 microstrip lines terminate the radial modes of the ceramic in its characteristic impedance of 1.34 Ω. The signals from the four pick-off points are combined into one 50 Ω output with a microstrip resistive combiner circuit fabricated on a 31 mil thick teflon circuit board. The teflon board is wrapped around and clamped to the gap. To flatten the impedance of the ferrite loaded cavity, several types of ferrite are used along with toroidal shaped microwave absorbing material. The transfer function of the detector is flat to about 1db from 3 KHz to 6 GHz as measured with a 50 Ω coaxial test fixture. Deviations in the transfer function occur when the voltage across the gap couples to, or drives, higher order modes inside the pipe.

SIGNAL PROCESSING

A typical signal received from the wall current monitor is indicated in Fig. 3. This voltage signal is acquired in the time domain using random repetitive sampling. It is possible from an ACNET console to have the oscilloscope enter an averaging mode where the oscilloscope calculates the average of the most recent data with the previous values in the same time slot. The number of averages can be varied from 1 to 32, each additional average requires roughly 100 msec.

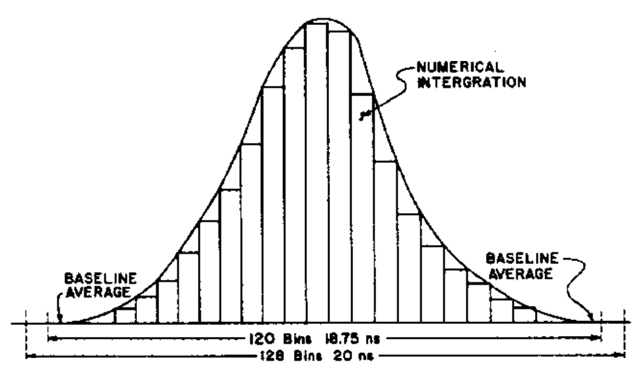

Fig. 3 Schematic of Bunch Voltage Profile.

After the complete signal has been acquired, one finds the number of particles ,N, that produced the signal from equation (3), below.

$$N = \frac{\int V*dt}{R*e*F} \tag{3}$$

e = charge on an electron
R = equivalent gap impedance
V = Ibeam*R, the detector voltage

The attenuation of the cable, splitters, and calibration of the sampling scope are included in the constant F. The integral of the voltage signal over time is then found by numerical integration after a background subtraction. The background subtraction utilizes a linear interpolation between the average of bins 5 through 9 and the average of bins 116 through 120 (the first four and last four bins are ignored as they fall in neighboring buckets).

The sigma of the distribution is determined from the numerical values in the normal manner. For ease of interpreting non-gaussian shaped distributions, the 50% and 90% widths are also calculated from the numerical data and presented to the host computer.

RESULTS

The capability of the system to operate in different modes allows several operational uses. In the Fast Measurement Mode [3] one uses the system to monitor the transfer process of protons and p-bars from the Main Ring to the Tevatron using a restricted set of calculated parameters. In the Setup Mode one can investigate the relative population of the "satellite" bunches after coalescing. Additionally the system is used to calculate the relevant parameters for each bunch during a store and save them on a computer disk for later analysis. This data, which is used for luminosity calculations can be checked for internal consistency. The precision of the intensity measurement is typically better than .5%. However, a calibration discrepancy of 1.3% exists between oscilloscope vertical gain settings [4]. As mentioned above, the accuracy of the system was checked with a known signal input. In addition, there have been several measurements comparing the SBD with a direct current monitor. The best measurements involve using the superdamper to remove unwanted beam, d.c. beam and coalescing satellites, then comparing the SBD with the direct current monitor. The agreement is typically within 5%. This close agreement was achieved only by the careful attention paid to detailed characteristics of each component in the system.

SUMMARY

The SBD system has been successfully used to monitor colliding beam operations at Fermilab. The current 5% accuracy in measuring single bunch intensity demonstrates the excellent fidelity and bandwidth of the system. The precision of .5% indicates the accuracy could be improved.

The design of a resistive wall monitor with 3 KHz to 6 GHz bandwidth and less than 1db amplitude variation is presented. In addition the use of microwave absorber inside the vacuum chamber to reduce noise is discussed.

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